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Seismic Assessment of the Sellafield B38 Mobile Caves

Warren Price BEng (Hons), CEng, FIMechE

Lead Technologist Structural & Seismic Modelling,
National Nuclear Laboratory, Warrington, UK. e-mail: warren.price@nnl.co.uk

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1 ABSTRACT

As part of activities to decommission the B38 facility at Sellafield, special purpose plant known as Mobile Caves have been designed, enabling the removal of waste from concrete silos, and movement to downstream plants for further processing. Three of such items of equipment are to be deployed designated SEP1, SEP2, and SEP3, each one moving between several silos and retrieving waste from it. Primarily due to shielding requirements the Mobile Caves are massively heavy structures, and despite being only moderately large in size (approximate envelope of 12m x 5m x 6m), a Mobile Cave has a design mass approaching 400 Te.

The National Nuclear Laboratory (NNL), set up during 2008 as part of the restructuring of British Nuclear Fuels Plc (BNFL), was requested to provide seismic analysis support to the project. This paper describes the modelling work completed by NNL in demonstrating that the Mobile Cave design is seismically robust, and meets its seismic safety case requirements.

2 INTRODUCTION

The B38 building at Sellafield originally consisted of six concrete silos with an overbuilding, and was commissioned in 1964. The first extension, a further six silos, was commissioned in 1974. A further building extension gave a total of twenty two silos. The silos were used for the storage of Magnox swarf, and miscellaneous beta gamma waste under water cover.

With the passing of time, storage of waste in B38 ceased and the plant lay dormant for many years. In the early 1990's concept designs that would facilitate the removal of the waste from the silos, and dispatch this to downstream plants started to be looked at by BNFL. This lead to the design of retrieval machines known as Mobile Caves. In the mid 1990's seismic analysis work which involved the use of finite element modelling, was completed by BNFL's Research & Technology (R&T) division. However, the Mobile Cave design evolved significantly over time, and after a period of mothballing of the project, it became clear that a fresh look at the historic seismic qualification work would be required. The National Nuclear Laboratory, which encompassed the old BNFL R&T division, was engaged by Sellafield Ltd (itself the main descendant company of BNFL) to provide analysis support for the seismic qualification of the Mobile Caves.

3 MOBILE CAVE

Each Mobile Cave consists of a primary structure, retrieval module, a skip transfer system, gamma gate, and operator bulge. Modules are attached to the structure to provide hydraulic, E&I, and hoisting capability, as well as numerous control and monitoring functions.

The Mobile Caves are built up from an inner box structure. Shielding panels which also double up as part of the structure, are attached to all four sides of the inner box by means of a large number of bolts. At one end of the inner box, a retrieval housing is attached to the top, once more through numerous bolts. The main structure alone contains in excess of 50 through wall penetrations to allow for various necessary functions. An operator bulge attached to both the primary structure and retrieval housing provides, via a shielded window, for an operator to utilise a hydraulic petal grab and various cutting tools and equipment. As waste is retrieved, it is placed into a skip which is itself located on a bogie which runs along rails within the inner box. When full, the waste skip is removed via a gamma gate to a removable flask located on the Mobile Cave structure. The flask is then removed by building crane and the waste transferred for treatment in downstream plants. During retrieval operations a Mobile Cave sits on eight elastomeric seismic isolation bearings (SIBs). A Pro-Engineer model of a Mobile Cave is shown in Figure 1. This figure gives an indication of the complexity of the design, with the primary structure barely visible beneath ancillary modules and access platforms.

Although being approximately only 12m long, the Mobile Cave with all of it ancillary modules and a full flask has a design mass of almost 400 Te. This is the equivalent mass of a 747-400 series jumbo jet fully laden at take off (Ref 1). This huge fabricated and bolted structure with some individual panels weighing in excess of 25 Te, had to satisfy safety case criteria demanding that it remained operational following a design basis earthquake (DBE), which for Sellafield site has a peak free field horizontal ground acceleration of 0.25g.

4 SEISMIC ANALYSIS

4.1 Historical Considerations

Historically within BNFL, seismic analysis of civil structures and buildings were completed by Buildings & Civils engineers, and seismic analysis of plant and equipment was completed by Mechanical Engineers located in separate teams within the company. Hence, the seismic analysis mathematical models of the B38 civil structure and the Mobile Caves were completed independently, and described as follows.

4.2 Building Structure

A finite element model was generated that included the building structure, concrete silos, and rails along which the Mobile Caves run. These models were created historically, and are maintained, by Sellafield Ltd. In this model, the Mobile Caves were represented as rigid “bricks” with the same mass and centre of gravity location as the Mobile Cave itself. The response spectrum and time history analysis output from this work include the three orthogonal seismic accelerations at the Mobile Cave centre of gravity, enveloped for multiple retrieval locations. The centre of gravity accelerations provided input to the work described in this paper, which was the detailed qualification of the Mobile Cave structure, work that was completed by NNL.

4.3 Mobile Cave Finite Element Model

A finite element model of the Mobile Caves was built using the proprietary code Ansys (Ref 2). Due to the thickness of the panels, Ansys solid elements ‘solid45’ were used for the vast majority of the structure. Shell elements where used where possible, for example, on the part of the under-section which was built up from thinner plate, and some of the internals.

The Mobile Caves are built up from an inner box structure, with shielding panels bolted to the inner box also acting as part of the structure itself. As noted, numerous bolted connections attach the structural shielding to the inner box. The key consideration with such a heavy structure is the transfer of load through such bolts. To simulate load transfer, in all locations where bolted connections have been made between separate parts, co-incident nodes have been positioned in the model, and these are coupled in the three translational degrees of freedom. By ensuring that coupled nodes exist in the exact location of every bolt, a detailed picture of bolt load transfer was enabled.

To ensure that the effect of prying was included in the bolt load analysis, Ansys 3D surface-to-surface contact elements ‘conta173’ and ‘targe170’ were used between mating faces. Assessment of the bolts did not account for the affect of surface friction between mating parts caused by bolt preload. This approach is conservative as it provides for simulation in which all loads pass directly through the bolts, with no credit taken for load transfer through friction.

The SIBs were modelled using Ansys ‘beam4’ 3D beam elements and ‘shell63’ shell elements. Hand calculations determined appropriate section and material properties required in the model in order to replicate the known stiffness properties of the SIBs. Before inserting these calculated values into the main structural model, simulation of the SIBs in a separate finite element model was used to confirm that the calculated properties correctly replicated the SIB stiffness. In the main model each SIB was constrained in six degrees of freedom at its base, corresponding to the boundary conditions imposed by the rail.

Since the primary objective of this analysis is to assess the performance of the primary structure under seismic load, the key requirement of the model was to capture all of the mobile cave mass and to replicate the location of the assembled Mobile Cave centre of gravity location as calculated through a detailed Pro-Engineer model created by the design team. In this particular assessment there was no requirement to provide a detailed analysis of various ancillary modules attached to the primary structure although these are completed in separate analyses. Hence, the analysis described here purely assessed the performance of the primary structure. As can be seen from Figure 1, the Mobile Cave is extremely complex and for this reason, the approach taken in the model was to include only the mass of attached modules weighing 2 Te or more. Hence, twelve masses were positioned in the model at the centre of gravity locations for the individual modules. The masses were modelled using Ansys 3D 'mass21' elements, and attached back to the main structure by means of stiff, light beams – Ansys 'beam4' 3D beam elements were used to achieve this. The remaining mass from items not explicitly included in the model was accounted for by uniformly smearing the mass across the primary structure. This method ensured that the overall centre of gravity location of the assembled Mobile Cave was replicated in the model as closely as possible. Checks revealed that the centre of gravity location calculated from the Pro-Engineer model, and that calculated in the finite element model agreed very closely.

A plot of the finite element model, with ancillary modules removed for clarity is shown in Figure 2. This figure also shows a section through the model. Due to the fact that the inner box structure is generally hidden from view by the outer structure/shielding, Figure 3 shows this part of the structure separated out from the rest of the model.

4.3.1 Seismic Loading

Modal analysis confirmed the Mobile Cave to be a seismically rigid structure. There are only two modes of vibration below 50 Hz. Both modes are horizontal with one at 36.4 Hz and the other perpendicular to it at 45.1 Hz. These are both above the flexible range cut off frequency, and neither mode has participating mass greater than 45% of the total structure mass. It is usual in seismic analysis to complete a response spectrum analysis and appropriate combination of modes to derive structural results. Response spectrum analysis adds no particular value when considering rigid structures since all modes act in phase and the assessment tends towards an equivalent static analysis using the Zero Period Acceleration. Additionally, due to historical issues described above only seismic accelerations at the Mobile Cave centre of gravity were available to NNL. For these reasons an equivalent-static seismic analysis was completed, with seismic accelerations applied to each of the three orthogonal directions.

Ref 3 paragraph 3.2.7.1.2 provides for two methods of combining spatial components of earthquake responses. The first method combines earthquake response using Square Root Sum of the Squares (SRSS), Ref 3 equation 3.2-25. ie.

$$R = \pm\sqrt{\sum_i R_i^2} \qquad [1]$$

where R is the combined co-directional response i = 1, 2, 3 for the two horizontal components and one vertical component of earthquake motion.

In the second method, responses are combined using the 100-40-40 rule Ref 3 equation 3.2-26, in which it is assumed that when one earthquake directional response is at its maximum, the other two directions will be at 40% of their maximums. All possible combinations of the three earthquake components R_1, R_2, and R_3, including variations in sign need to be evaluated. ie.

$$R = \pm\left[R_1 \pm 0.4R_2 \pm 0.4R_3\right] \qquad [2]$$

and $$R = \pm\left[R_2 \pm 0.4R_3 \pm 0.4R_1\right]$$

and $$R = \pm\left[R_3 \pm 0.4R_1 \pm 0.4R_2\right]$$

Hence, all permutations of the above produce 24 separate load cases.

In each of the individual load cases produced by [1] and [2] the seismic component must be also combined with self weight.

4.3.2 Allowable Stress

Strictly speaking, defining allowables for the Mobile Caves in terms of ASME III is difficult, since the primary intent of ASME III is to assess pressure retaining equipment, piping and supports. The Mobile Cave is neither a pressure retaining structure such as a pressure vessel, nor a support. The use of ASME III was however, retained in this assessment as there are parts of the code that can be used in principle to evaluate performance of both the main structural items, and the bolts holding them together. If the stresses are within the allowable values this ensures that the structure will not fail or collapse.

For the seismic assessment of structural items, ASME III subsection NC allowables (Ref 4) have been used, this section of the code applying to parts of a nuclear system that are important to safety and designed for such functions as emergency core cooling and post accident fission product removal. The requirement for the Mobile Cave's primary structure to safely survive an earthquake can convincingly be viewed as analogous to the safe operation of equipment required to safely remove fission products, although clearly with much less severe consequences of failure in the case of the Mobile Caves.

Paragraph NCA-2142.4 of Ref 5 defines four service levels A, B, C, and D for plant and equipment in which Service Level A corresponds to normal operating conditions. Service Level B applies to a deviation from normal operating conditions. Service Level C is for an event of low probability and Service Level D describes an event of extremely low probability such as a major earthquake in the UK. With Service Level D the structure is allowed to yield and there will be structural plastic deformation, meaning the equipment may not be operable after the event, however structural failure will not occur. With Service Level B there is no plastic deformation and the equipment would remain operable. It is conservative therefore to assign allowable stresses associated with Service Level B rather than Service Level D.

Article NC-3000 of Ref 4, paragraph NC-3112.3, requires that Design Mechanical Loads are considered. Included in these are self weight, attachment loads, and seismic loads. Each of these is considered in the Mobile Cave assessment. While membrane stress associated with a pressure retaining component will not feature in the Mobile Cave analysis, local membrane stress effects and bending stress caused by the Primary loads do feature. The allowable for these are defined in terms of the material property S_m which is the Design Stress Intensity and calculated in accordance with ASME III rules. Hence, allowable stress intensity (membrane plus bending) for the Mobile Cave structure must be limited to:

$$P_m + P_b = 1.5.\ k.\ S_m \qquad \text{(Ref 4 Paragraph 3217(d))}$$

where for Service Level B, $k = 1.1$ (Ref 4 Table NC-3217-1)

The calculation of S_m is based on the least of one third of the minimum value of tensile strength, or two thirds of the minimum value of yield strength (Ref 5, paragraph 2-110).

Acceptable bolt performance has been calculated based on the ASME interaction equation between bolt tension and shear as defined in Ref 6, paragraph NF-3324.6(3)(a), ie.

$$\frac{f_t^2}{F_{tb}^2} + \frac{f_v^2}{F_{vb}^2} \leq 1 \qquad [3]$$

where,

f_t is the calculated bolt tensile stress

f_v is the calculated bolt shear stress

F_{tb} is the permissible bolt tensile stress

F_{vb} is the permissible bolt shear stress

Both F_{tb} and F_{vb} are defined by Ref 6, paragraph NF-3324.6(2), with for Service Level B, an enhancement factor of 1.15 (Table NF-3225.2-1)

5 RESULTS

In the case of the Mobile Caves, the size and sheer volume of detailed post processing requirements resulted in the 2 load cases required by the SRSS method (self weight ± SRSS seismic) being selected for completion of seismic analysis, as opposed to the 24 required using 100-40-40.

Stresses in all parts of the Mobile Cave structure were determined. Stresses calculated from the model were expressed as stress intensities, since these are to be compared to the ASME code allowable, which are also specified as stress intensity. Stress intensity is the equivalent intensity of combined stress, defined as twice the maximum shear stress. In other words, the stress intensity is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. The use of stress intensity is conservative.

Stresses for each load case (three seismic, and self weight) were calculated and combined as described in Section 4.3.1. The calculated stresses were generally very low as would be expected for a structure fabricated from very thick plates. Although many in number, penetration holes made little or no difference to the stress distribution. Good margins of safety were demonstrated against ASME III NC (Ref 4). A plot of stress distribution in the inner box viewed from the underside, is shown in Figure 4. An increase in stress is noted in locations of bolted connections but for the most part the stress level is very low.

Loads transferred between parts via coupling of connected parts at coincident nodes are the loads that must be transferred by the bolts. By isolating the various assemblies from the rest of the model in post-processing runs, the individual bolt loads were extracted and used as the basis for calculating bolt stresses. Margins of safety for the bolts were in most cases very large. Weld stresses were assessed by a combination of FE model results and hand calculation, and once more, good margins of safety were recorded.

With all analysis work, one is responsible to ensure that there is as much confidence in the results as is reasonably possible, and for this reason further analysis was undertaken. Using the 100-40-40 method previously described, 24 load cases were run, each combined with self weight, and the reactions of the eight SIBs interface at the rails recorded. These were then compared with the reactions for the 2 load cases from the SRSS method each combined with self weight. For each set of nodal reactions at the SIBs, the numerical difference between the maximum values produced by SRSS and the maximum values produced by 100-40-40 were recorded, and denoted $_{max}$. Similarly, for each set of nodal reactions at the SIBs, the numerical difference between the minimum values produced by SRSS and the minimum values produced by 100-40-40 were also recorded, and denoted $_{min}$. For each of the eight nodal reactions it was found that $_{max}$ and $_{min}$ derived from the model were virtually the same value, but of opposite sign. That this is a desirable result is shown as follows:

Let,

SRSS seismic	=	SRSS
Self Weight	=	Swt
Maximum of 100-40-40	=	M
Minimum of 100-40-40	=	-M (all signs opposite from that giving the maximum)

Then,

Self Weight + SRSS seismic	=	Swt + SRSS
Self Weight – SRSS seismic	=	Swt - SRSS
Self Weight + (100-40-40) max	=	Swt + M
Self Weight – (100-40-40) min	=	Swt - M

Difference on maximums

$$_{max} = (Swt + M) - (Swt + SRSS) \quad = M - SRSS$$

Difference on minimums

$$_{min} = (Swt - M) - (Swt - SRSS) \quad = -M + SRSS$$

Hence, it is shown that for a linear analysis $_{max}$ and $_{min}$ should be equal and opposite. Hence, confidence in the accuracy of the results was achieved through the use of the two methods noted in Ref 3.

By considering the range of values for each directional component, it can be shown that the 100-40-40 combination method generally produces higher estimates of maximum response than the SRSS combination method by as much as 15 percent, while the maximum under-prediction is about 1 percent. The difference will depend on the relative size of the three orthogonal accelerations, with the maximum difference occurring when the seismic accelerations are in the ratio 100-40-40. Since the Mobile Cave accelerations were by coincidence, almost precisely in the ratio 100-40-40, the maximum percentage difference between the two combination methods was expected. Post processing results confirmed this to be the case with differences between methods ranging between 9 and 14 percent for the vertical direction reaction force.

6 CONCUSIONS

By means of finite element modelling and supplementary hand calculations, seismic qualification of the massively heavy B38 Mobile Caves has successfully been achieved. Equivalent static methods have been used for the structural analysis, in which seismic loads were combined using the SRSS method. Independent validation and confidence in the results has been achieved using the 100-40-40 combination method.

All bolted and welded joints were assessed and shown to be acceptable, and the stress in each individual bolt was examined. Stresses in all parts of the structure were determined and compared to the ASME III code subsection NC allowable values for the material. The Mobile Cave primary structure is predicted to experience stresses within the material elastic limit during the design basis earthquake, with no permanent deformation resulting from seismic loading, thus satisfying safety case requirements. The assessment has confirmed the seismic robustness of the structure, and all shielding and containment will be maintained in the event of a 0.25g DBE event.

7 FIGURES

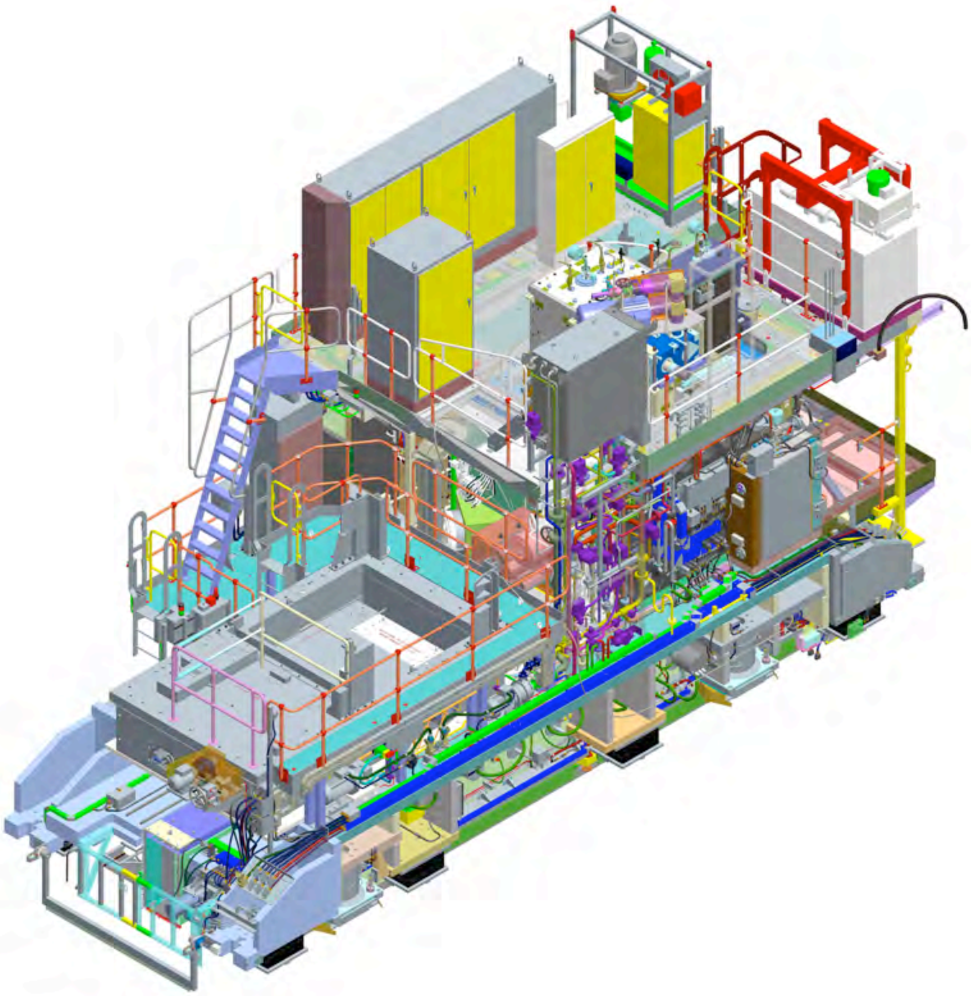
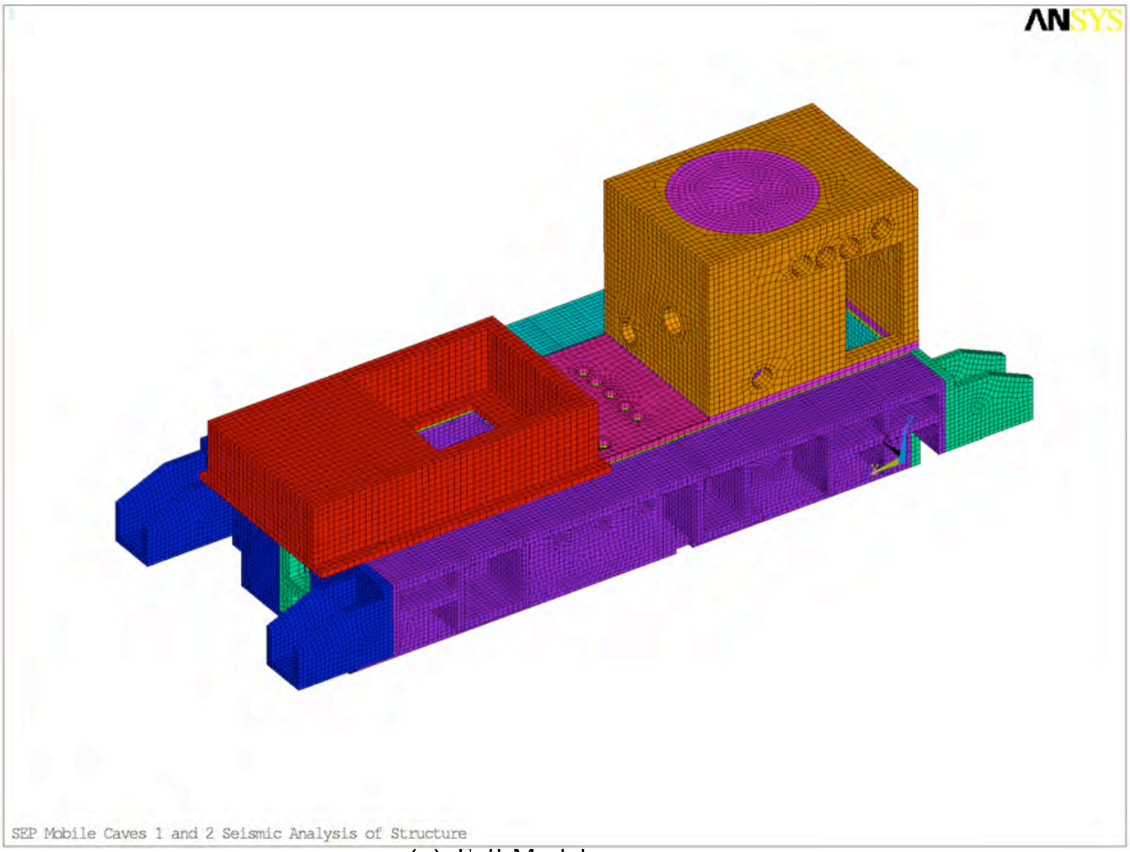
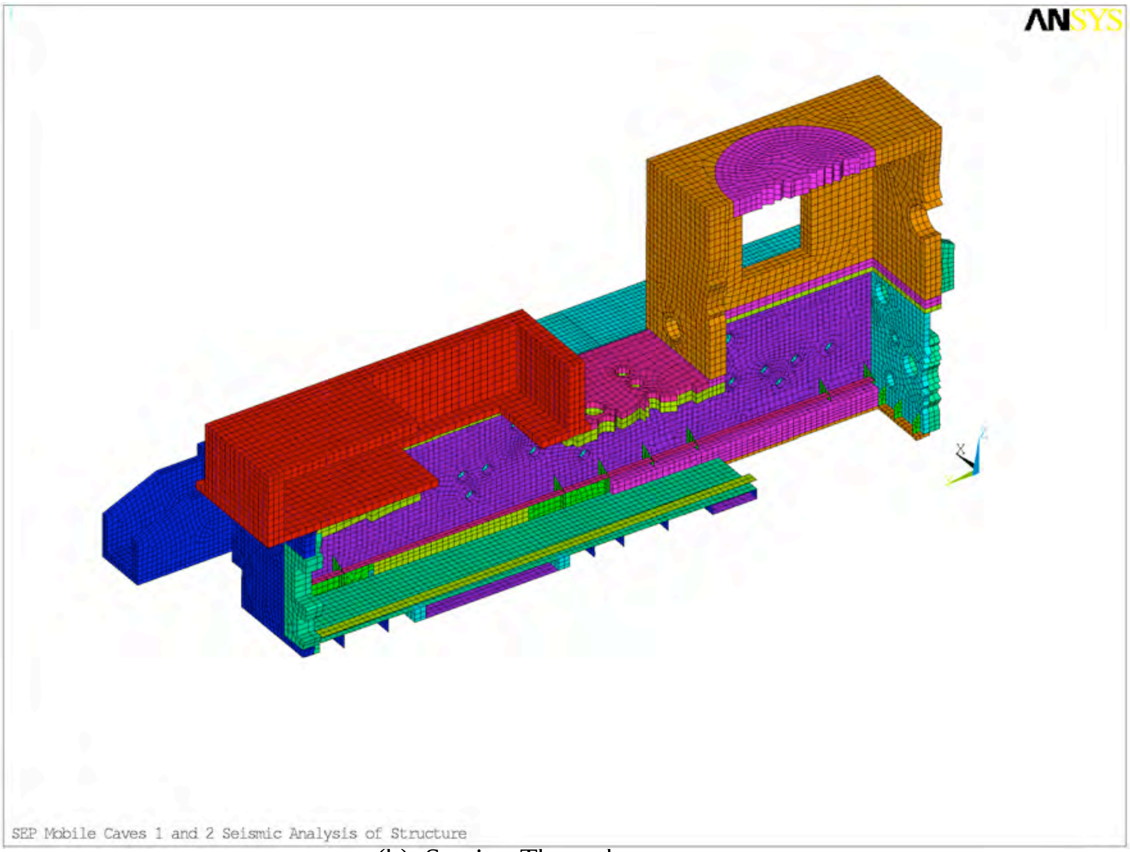


Figure 1 - Isometric View of the Mobile Cave produced by Pro-Engineer



(a) Full Model



(b) Section Through

Figure 2 - Finite Element Model of Mobile Cave Primary Structure

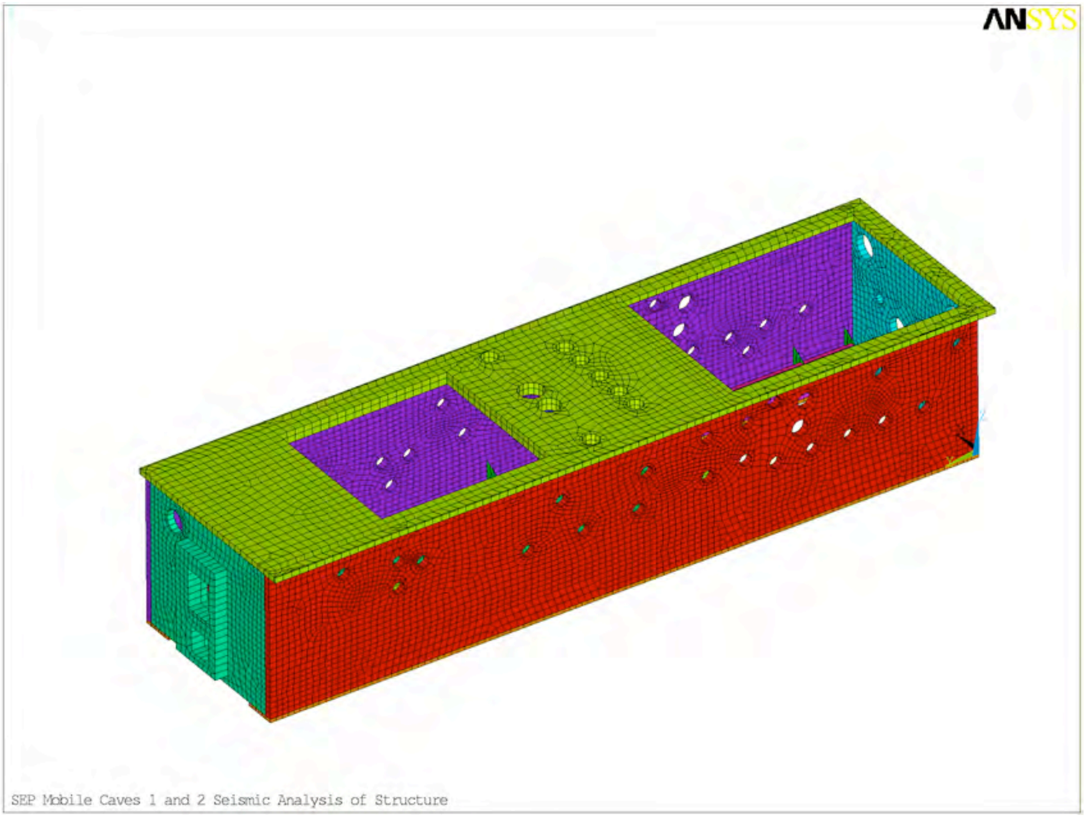


Figure 3 - Finite Element Model Inner Box Structure

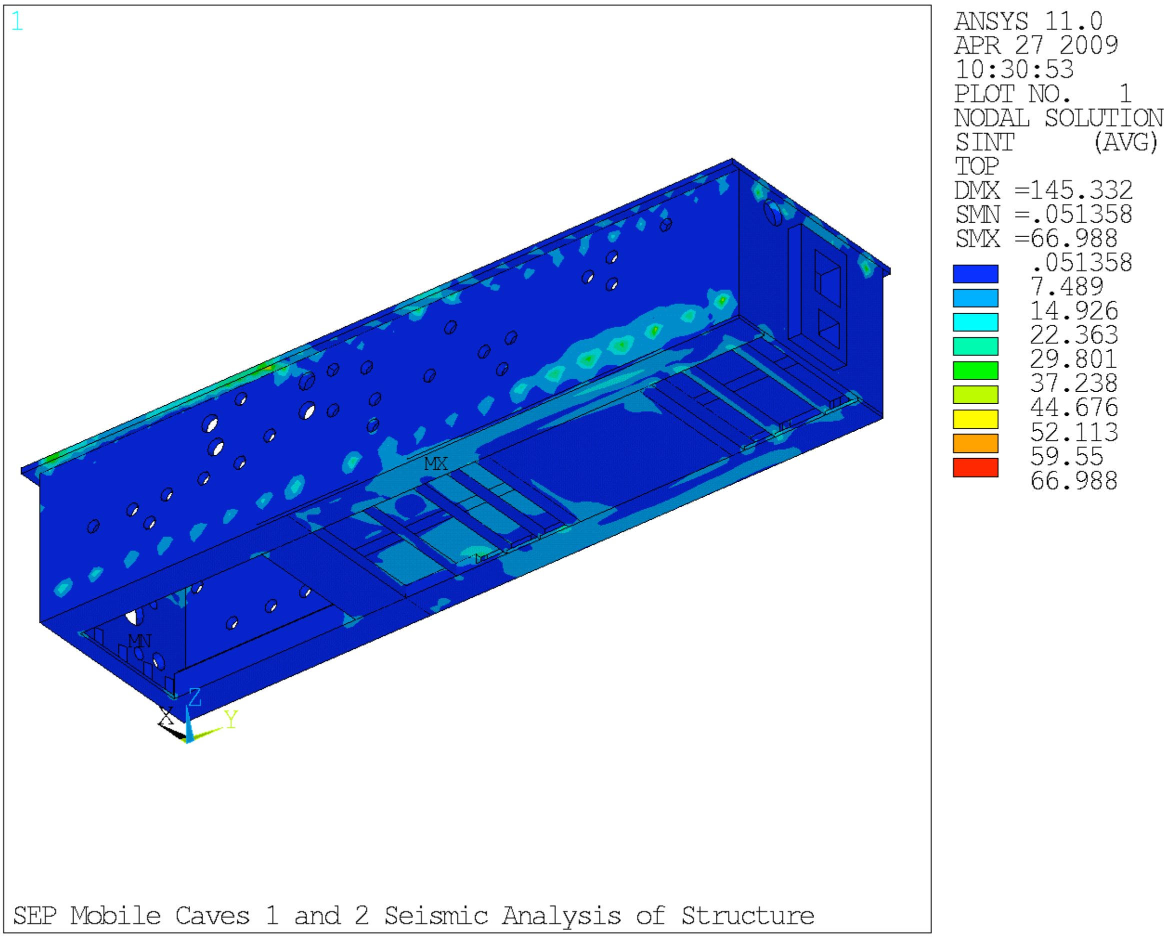


Figure 4 - Distribution of Stress Intensity (MPa) in Inner Box

REFERENCES

1. Boeing website http://www.boeing.com/commercial/747family

2 ANSYS Inc, Southpointe, 275 Technology Drive, Canonsburg, PA 15317. USA

3. American Society of Civil Engineers, 2000, ASCE-4-98 "Seismic Analysis of Safety-Related Structures and Commentary." ISBN 0-7844-0433-X

4. American Society of Mechanical Engineers (ASME), 2007 edition. Boiler and Pressure Vessel Code, Rules for Construction of Nuclear Power Plant Components, Section III, Division 1, Subsection NC, "Rules for Construction of Nuclear Facility Components – Class 2 Components".

5. American Society of Mechanical Engineers (ASME), 2007 Edition. Boiler and Pressure Vessel Code, Rules for Construction of Nuclear Power Plant Components, Section III, Division 1, Article NCA-2000, "Mandatory Appendix 2 Basis for Establishing Design Stress Intensity Values for Tables 2A, 2B, AND 4, and Allowable Stress Values for Table 3".

6. American Society of Mechanical Engineers (ASME), 2007 edition. Boiler and Pressure Vessel Code, Rules for Construction of Nuclear Power Plant Components, Section III, Division 1, Subsection NF, "Rules for Construction of Nuclear Facility Components - Supports".